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Abstract

We have measured the muon momentum distribution in charged pion decay in flight in order to search for a small branching fraction η of pion decays $\pi^+ \rightarrow \mu^+ + X$, in which a heavy neutral particle X with a mass of 33.9 MeV would be emitted. The upper limit of η at a confidence level of 95 % is found to be $2.6 \cdot 10^{-8}$.

Recently an anomaly in the time distribution of neutrinos from a pulsed beam-stop source was reported by the KARMEN collaboration [1], with a speculative explanation that these events could originate from a rare pion decay process,

$$\pi^+ \rightarrow \mu^+ + X, \quad (1)$$

where X is a heavy neutral particle with a mass of 33.9 MeV. The KARMEN collaboration estimated values of the branching fraction of this decay mode down to 10^{-16} , depending on the lifetime τ_X of such a particle. Barger et al. [2] pointed out that part of this range can be excluded by consideration of other experiments. They determined the allowed range for the branching fraction to be between $6 \cdot 10^{-5}$ and $3 \cdot 10^{-8}$. However, in a recent erratum [3] they corrected their earlier findings such that almost the entire range published by the KARMEN collaboration is now allowed.

According to Ref. [1] the flight time of the hypothetical X -particles for a path of 17.5 m is $(3.60 \pm 0.25) \mu\text{s}$. This, together with the pion and muon masses of Ref. [4], corresponds to a rest mass of

$$m_X = 33.9057 \pm 0.0009 \text{ MeV}, \quad (2)$$

which is very close to the mass difference between the charged pion and the muon, $m_{\pi^+} - m_{\mu^+} = 33.91157 \pm 0.00067 \text{ MeV}$. Because of the small muon kinetic energy from such a decay mode, these particles could not have been detected in heavy neutrino searches with pions decaying at rest [5]. However, for the decay in flight, the small Q -value has several advantages: firstly, the velocity of the muon is very close to the velocity of the original pion ($p_\mu \approx p_\pi \cdot m_\mu/m_\pi$), secondly, the flight direction of the muon differs only slightly from that of the pion, and thirdly, the

specific energy loss of the muon is almost the same as that of its parent pion. This enables one to use the beam-line itself as a spectrometer to separate the decay muons from other particles as well as muons originating from the main π^+ -decay mode. An added advantage is that pions themselves can be used to set up counter thresholds and timing in order to calibrate the system for optimal detection of muons from the decay (1).

In our measurement of the momentum spectrum of muons from π^+ -decay in flight we used the high intensity pion-channel $\pi E1$ at PSI, together with a scintillator hodoscope. Shortly before we started this measurement we learned of a similar experiment by another collaboration at PSI [6] who use the decay in flight, and the Low Energy Pion Spectrometer (LEPS) with a momentum resolution of $\Delta p/p=0.1\%$ and an angular acceptance of 150 mrad.

In our set-up we took advantage of the fact that a "quadrupole channel", i.e. a beam-line consisting of dipoles and quadrupoles only, accepts muons preferably in the forward or backward direction in the pion center-of-mass system. The momenta of these muons differ strongly from those of the decay (1), whereas the muons from the main decay mode which are emitted sideways are suppressed because of the limited angular acceptance of the beam-line.

The lay-out of the experiment is shown in Fig. 1. The beam-line consists of three parts: (i) The first part from the pion production target to the dipole magnet ASY, used to transmit the π^+ . (ii) The pion decay region between the dipole magnets ASY and ASL. (iii) The muon transmitting and analyzing part from the dipole magnet ASL to the hodoscope.

Positive pions of 120.0 MeV/c with a momentum spread of 1.5 % (fwhm), de-

fined by the collimator opening at the dispersive focus in the dipole magnet ASY, were used (Fig. 1). The momentum choice was governed by the need for a good particle (positrons, muons, pions) separation in time-of-flight at the point of detection. About 1/3 of the pions entering the decay region between the two dipole magnets ASY and ASL (cf. Fig 1.) decay in it. By tuning the whole beam-line to pions of 120.0 MeV/c a measured intensity of $1 \cdot 10^7 \pi^+/\text{s}$ at a primary proton current of 1 mA was achieved at the initial point of detection (pt. 9, Fig. 1).

At a pion momentum of 120.0 MeV/c and a momentum spread of 1.5 % (fwhm) muons from the decay of Eq. (1) have a momentum distribution centered at 90.8 MeV/c with a width of 1.8 MeV/c (fwhm). Their emission angle with respect to the pion in the laboratory system is $0 \leq \theta \leq 6 \text{ mrad}$ whereas muons of about 90.8 MeV/c from normal pion decay have a decay angle close to the maximum of 334 mrad.

During the data-taking the first part of the beam-line up to the decay region was tuned to 120.0 MeV/c, with the quadrupole doublet (QTH51, QTH52) set to focus pions onto the momentum defining slit at the center of dipole ASY. The last part of the beam-line after the decay region was set to momenta around 91 MeV/c (see below). The quadrupole doublet (QSL53, QSL54) was set to focus muons from the decay (1) onto a counter telescope (S0, S1), consisting of two 2 mm thick plastic scintillators located behind a lead collimator of opening $4 \times 4 \text{ cm}^2$. This opening was determined using the computer program DECAY TURTLE [7] with a mass of 33.9057 MeV (cf. Eq. 2) for the neutral particle.

The particles downstream of the telescope passed a spectrometer consisting of three quadrupoles and a dipole magnet with a deflection angle of 50° and a dispersion of 2 cm/%. A hodoscope placed at the end of the beam-line and consisting of

10 plastic scintillation counters, each 3 cm wide, 17 cm high and 5 mm thick, was used for the momentum analysis.

We used the standard π E1 vacuum system, which extends to a mylar window 15 cm downstream of QSL54. In addition, the triplet (QSK51, QSL55, QSK52) had a 2.2 m long vacuum chamber with a mylar window at each end. In the dipole ASK and from there to the hodoscope, the beam particles had to pass through about 2.9 m of air. As a consequence, the pion beam for a 120.0 MeV/c tune at the hodoscope had a spot size of 9 cm (fwhm). If the whole beam was tuned to 91.0 MeV/c muons, the observed spot size at the hodoscope was even larger (10.5 cm), as expected.

The time-of-flight separation of the particles was checked by tuning the whole beam-line to 120.0 MeV/c. The positrons, muons and pions from the production target to the telescope (S0, S1) take respectively 53, 71 and 81 ns, and can be clearly separated using the 50 MHz radio-frequency of the accelerator (see Fig. 2a).

The corresponding distributions of the observed particles in a run of the search for the X-particles, in which the beam-line from ASL to the hodoscope was set to a momentum of 91.0 MeV/c, are displayed in Fig. 2b. There are three separate distributions which can be attributed to pions, muons, and positrons, respectively. Events around 0 to 2 and 18 to 20 ns on the horizontal and 24 to 27 ns on the vertical scale originate from pions, which fly with a momentum of 120.0 MeV/c from the target to the momentum slit in ASY. There they undergo slit scattering, lose about 29 MeV/c and follow the beam-line up to the hodoscope. Scattered positrons are found around 13 ns (horizontal scale) and 8 ns (vertical scale).

Muons appear between 15 and 23 ns on the vertical scale. Events between

10 and 15 ns on the horizontal scale can be attributed to muons which originate from pion decays in the vicinity of the pion production target (cloud muons) and move with a momentum of about 120 MeV/c along the first part of the beam-line. Again at the momentum slit they are scattered, so that they continue with about 91 MeV/c and are accepted by the second part of the beam-line. All these events can be clearly separated by time cuts from candidate X-events. The candidates are expected to show up in the muon band (vertical scale 15 to 23 ns) on the horizontal scale between 5 and 8 ns, i.e. approximately in those channels in which pions show up in Fig. 2a. Moreover, X-candidates should produce a peak in the hodoscope counters.

In order to search for such a peak we scanned the beam momentum in the second part of the beam-line, i.e. from ASL onwards. One scan consisted of 17 runs corresponding to the 17 momentum settings between 87.0 and 95.0 MeV/c in steps of 0.5 MeV/c. In total, we performed 7 such scans. As a normalization monitor we used the "proton signal" of the accelerator, a monitor proportional to the proton beam intensity. A run consisted of registering events for 1000 seconds at 1 mA of proton beam.

A peak produced by the hypothetical decay (1) would shift systematically with the hodoscope counter number. The position and the shape of such a peak were predicted from scans with pions and "cloud muons". In these scans the first part of the beam-line was set to 120.0 MeV/c for pions and to 90.8 MeV/c for muons, respectively. The second part was then scanned for pions between 118.0 and 122.0 MeV/c and for muons between 88.0 and 93.0 MeV/c in steps of 0.5 MeV/c.

The summed candidate X-muon events of all scans in one of the central ho-

doscope counters are displayed in Fig. 3. In our data, no peak is visible. As a study with DECAY TURTLE showed [7,8], the events in Fig. 3 are consistent, within fairly large uncertainties, with being due to muons which were emitted by pions and were scattered at the apertures of the beam-line elements.

From the scans with pions and cloud muons we know that in the hodoscope counters 1, 2, 9, and 10 only very few X-muon candidates can appear. We used the momentum scans of these hodoscope counters for the estimation of the background and found a hyperbola as the best fitting function. Such hyperbolas were also fitted to the data of the hodoscope counters 3 to 8 together with a distribution for the hypothetical X-muon candidates.

The height of the distribution predicted for an assumed branching fraction of 10^{-7} was multiplied with a parameter α which was varied in steps of 0.1 between -1 and +1. For each value of α the data were fitted by the hyperbola plus the expected distribution for muons from the decay (1), with five free parameters and typically 11 degrees of freedom.

The repeated scans differed in excess of the statistical uncertainties. In order to take into account these systematic uncertainties, such as drifts of the proton beam on the target and the resulting intensity changes of the pion beam, we multiplied the statistical uncertainties by a "scale factor". This factor was determined separately for each hodoscope counter so that the fitting function had a χ^2 -value of 1.0 per degree of freedom at the optimum value of α . The scale factors for the different hodoscope counters were between 1.00 and 1.43, with an average of 1.18. The summed χ^2 of all scans for the hodoscope counters 3 to 8 is displayed in Fig. 4. From the parabola fitted to the χ^2 -distribution of Fig. 4, we find the

branching fraction to be

$$\eta = \frac{\Gamma(\pi^+ \rightarrow \mu^+ + X)}{\Gamma(\pi^+ \rightarrow \mu^+ + \nu_\mu)} = (-0.40 \pm 0.23) \cdot 10^{-7}; \quad (3)$$

the uncertainty corresponds to one standard deviation. From this, using the "Bayesian approach" described in Ref. [4] (probability function is set to zero for negative, i.e. unphysical values of η) we find an upper limit of

$$\eta \leq 2.6 \cdot 10^{-8} \text{ (c.l. = 95 \%)} \quad (4)$$

This value is lower than the upper limit of $7 \cdot 10^{-8}$ (c.l. = 95 %) found by Bilger et al. [6] who had a significantly smaller total number of useful pions.

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Figure captions

Fig. 1: Experimental set-up. 1) central trajectory of 590 MeV proton beam; 2) pion production target (graphite, not to scale); 3) central trajectory of pion beam; 4) half-quadrupole magnets; 5) dipole magnets; 6) quadrupole magnets; 7) collimator defining the beam momentum acceptance; 8) concrete shield of proton channel; 9) scintillation counters S0, S1; 10) lead collimator; 11) scintillation counter hodoscope; 12) acceptance limiting collimator.

Fig. 2: a) Two-dimensional event distribution. All beam elements are set for 120.0 MeV/c. Horizontal axis: time-of-flight of the particles in the beam-line from the pion production target to the scintillation counters S0 and S1. Start signal is the coincidence S0-S1, stop signal is RF, the 50 MHz radio-frequency signal of the cyclotron. Time increases to the left. The absolute flight times are 53, 71 and 81 ns for positrons, muons and pions, respectively. Vertical axis: time-of-flight of the particles from the start counters S0 and S1 to one of the central hodoscope counters. Muons from the decay mode of Eq.(1) are expected to appear in the pion region of this plot when the second part of the beam-line is set to momenta around 91 MeV/c.

b) As Fig. 2a). Here the first part of the beam is set to 120.0 MeV/c and the second part to 91.0 MeV/c.

Fig. 3: Muon events in one of the central hodoscope counters. The uncertain-

ties are about equal to the size of the dots.

a) The curve is a hyperbola fitted to the points from momenta 87.0 to 95.0 MeV/c; the χ^2 is 10.0 for 12 degrees of freedom.

b) Here the dashed curve is a fit of a hyperbola plus a peak from the hypothetical decay $\pi^+ \rightarrow \mu^+ + X$ with a branching fraction of $2 \cdot 10^{-7}$; the χ^2 of the fit is 31.3 for 12 degrees of freedom. The solid curve is the hyperbola without the additional peak.

Fig.4: χ^2 for the summed momentum scans of the hodoscope counters 3 to 8, as a function of $\alpha \equiv \eta/10^{-7}$, where η is the assumed branching fraction for the decay(1). The total number of degrees of freedom is 66. The solid curve is a parabola fitted to the data points.

Fig. 1

Fig. 2

Fig. 3

MUONS PER 1000 MAS OF PROTON BEAM

MUON MOMENTUM [MeV/c]

Fig. 4